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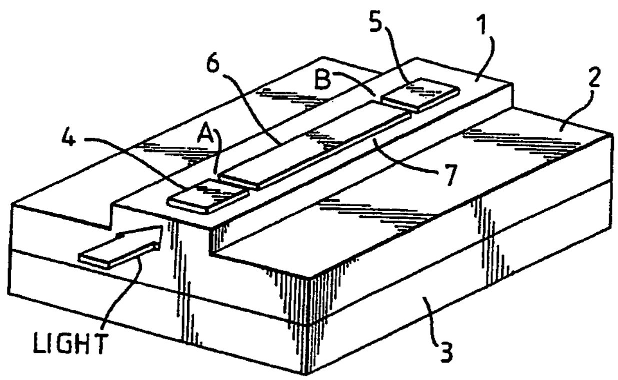
(54) **Silicon bipolar phase modulator**

(57) An electro-optic bipolar phase modulator comprises a laterally-confined waveguiding channel (1) formed in a lightly-doped silicon layer (2), and a heavily-doped silicon sub-layer (3) of opposite polarity. The modulator is provided with three electrodes (4, 5, 6) for controlling the carrier density within the channel (1), thereby modulating light propagating in the channel by varying the refractive index of the channel. The three electrodes (4, 5, 6) define a bipolar transistor structure. Modulation is achieved by alternating between first and second predetermined voltage regimes applied to the electrodes (4, 5, 6), the first predetermined voltage regime driving the bipolar transistor structure into the saturation mode, and the second predetermined voltage regime driving the bipolar transistor structure into the cut-off mode. The channel is fully open when the transistor structure is in the saturation mode, and fully depleted when the transistor structure is in the cut-off mode. Alternation between the predetermined voltage regimes is of a quasi-digital nature.

Fig. 1.



At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

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Fig. 1.

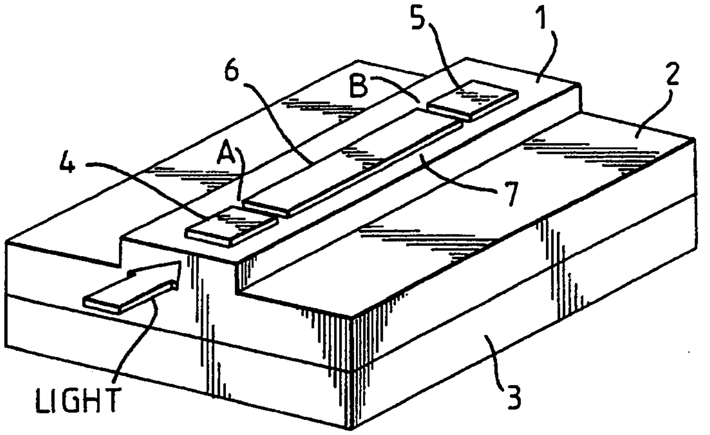


Fig. 2.

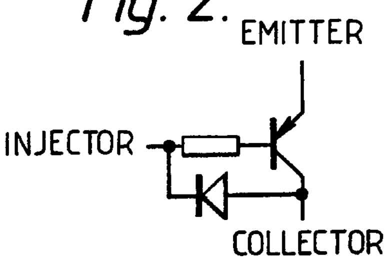
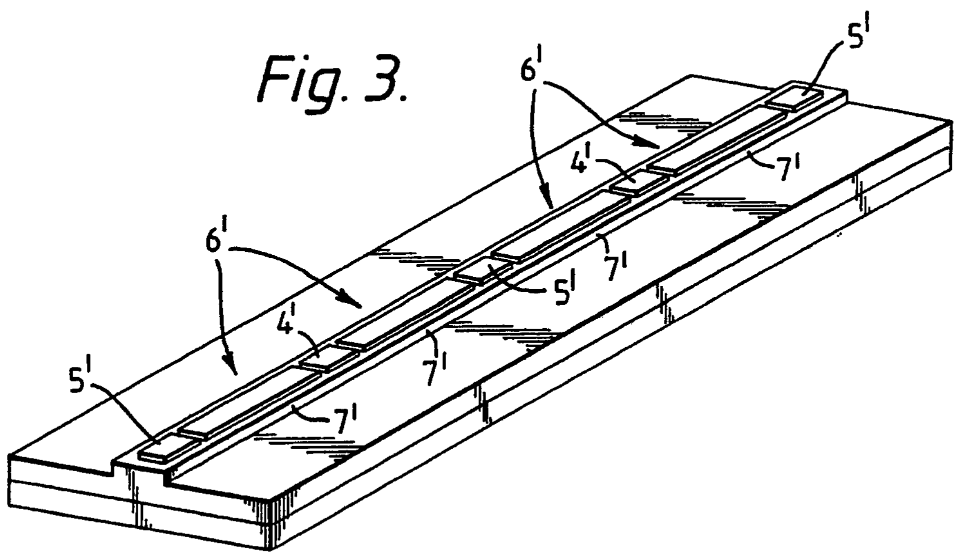


Fig. 3.



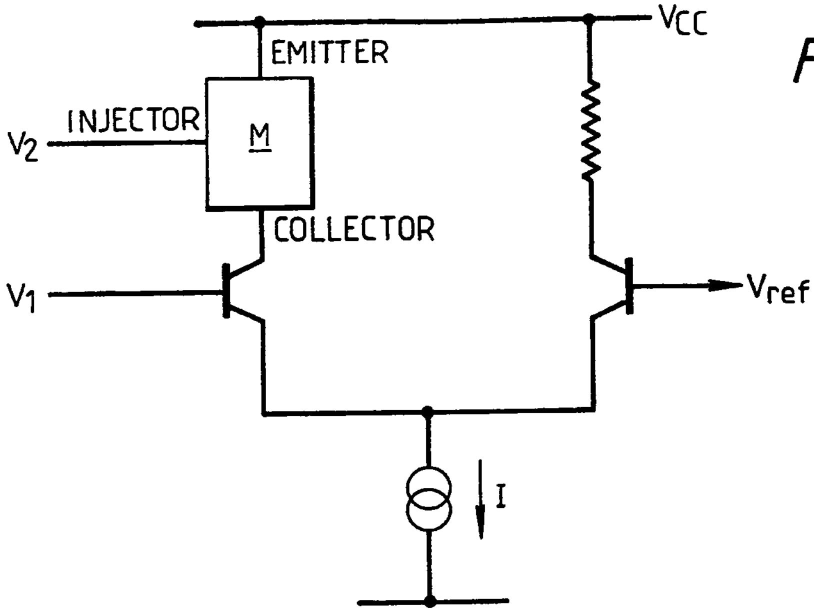

VCC
EMITTER
INJECTOR
V2
M
COLLECTOR
V1
Vref
I

Fig. 4.

Fig. 5.

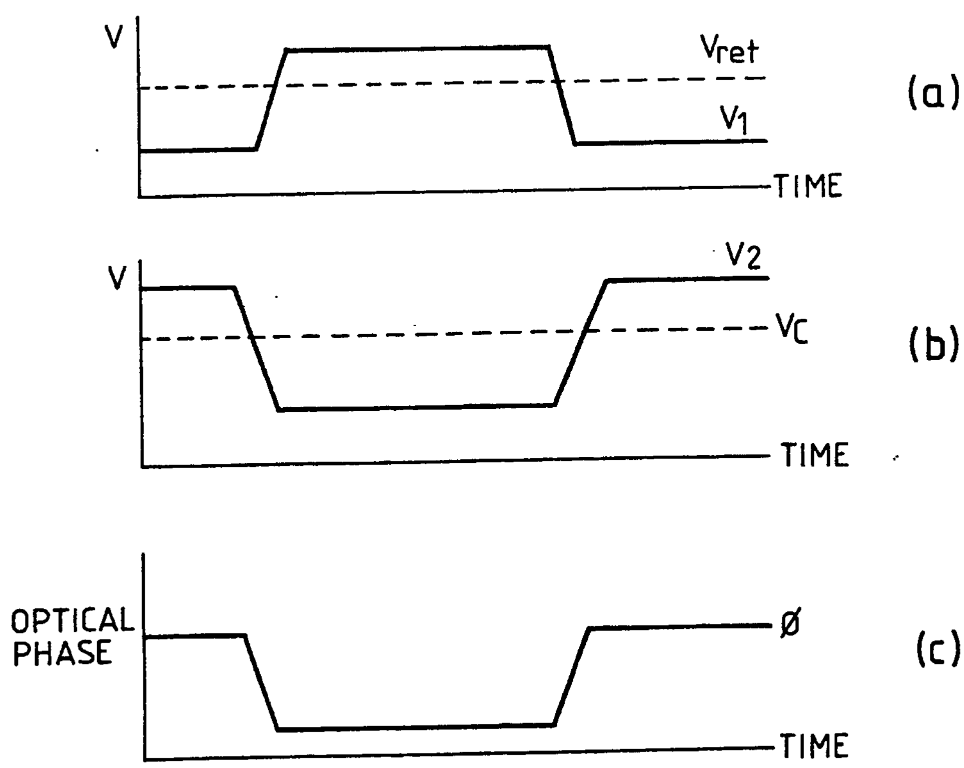

V
Vref
V1
TIME
(a)
V
V2
VC
TIME
(b)
OPTICAL PHASE
Ø
TIME
(c)

Fig. 6.

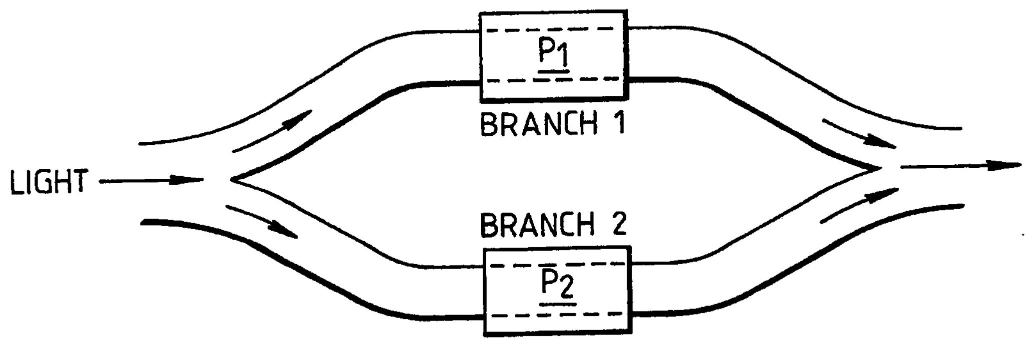

P1
BRANCH 1
LIGHT
BRANCH 2
P2

Fig. 7.

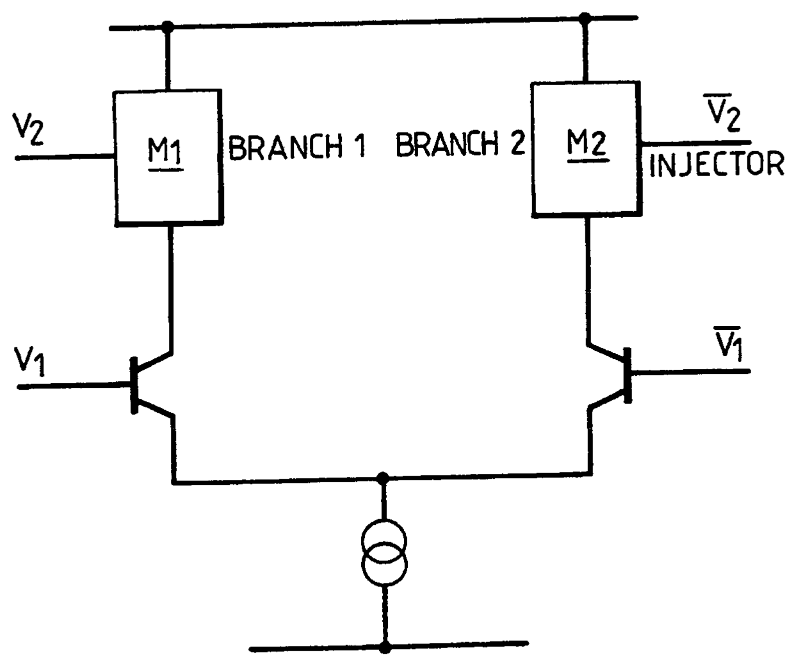
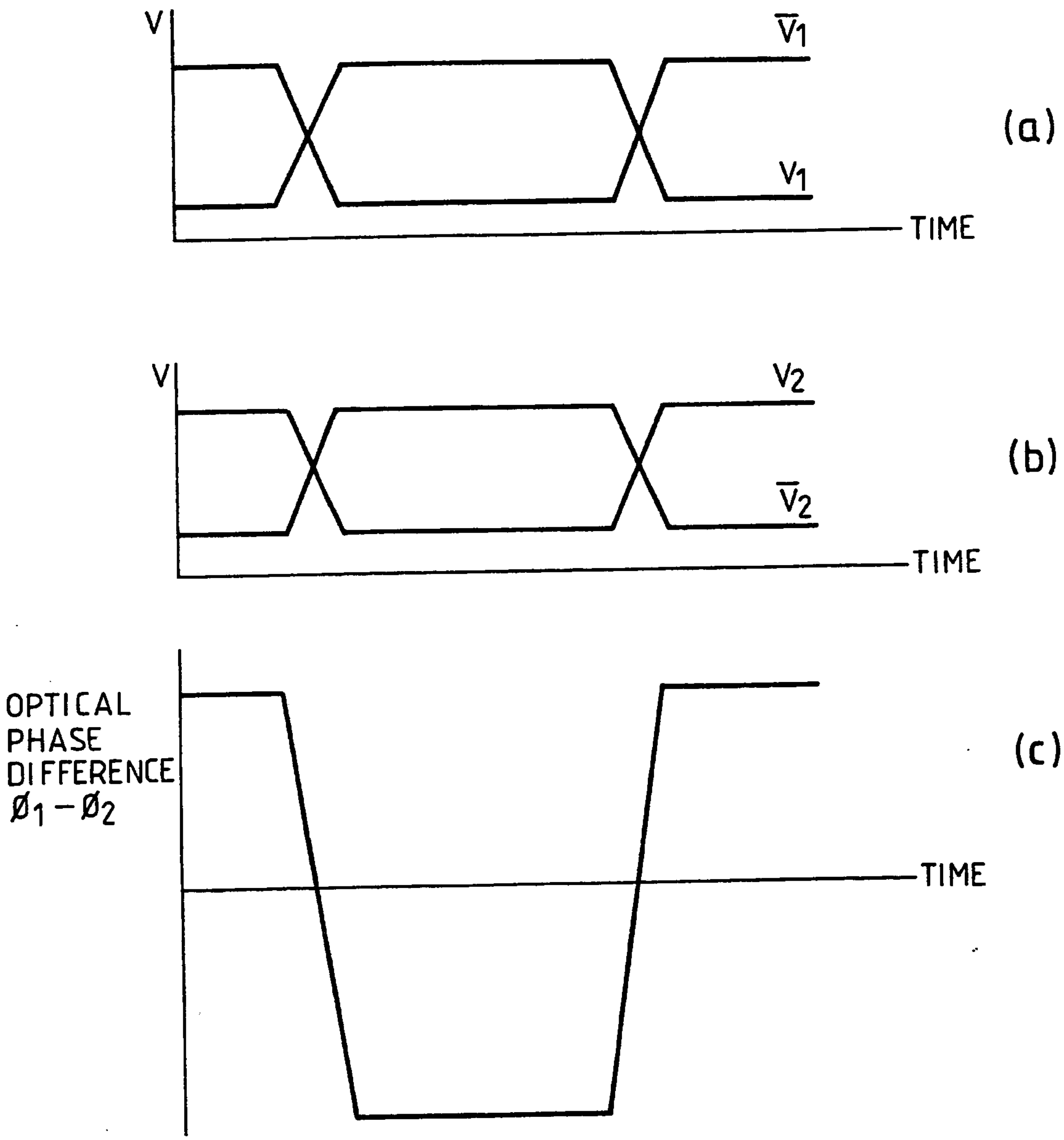

V2
M1
BRANCH 1
BRANCH 2
M2
V̄2
INJECTOR
V1
V̄1

Fig. 8.


V
$\overline{V}_1$
V_1
TIME
(a)
V
V_2
$\overline{V}_2$
TIME
(b)
OPTICAL PHASE DIFFERENCE $\phi_1-\phi_2$
TIME
(c)

SILICON BIPOLAR PHASE MODULATOR

This invention relates to a silicon bipolar electro-optic phase modulator, and in particular to a modulator for a silicon rib waveguide.

A silicon rib waveguide has a waveguiding channel defined by a lightly-doped silicon layer and laterally and vertically confined by suitable means. For example, the waveguiding channel can be vertically confined by a heavily-doped silicon sub-layer. In this case, a mesa-etched rib in the lightly-doped silicon layer provides lateral confinement for the waveguiding channel. Alternatively, the waveguiding channel may be buried, or vertical confinement may be achieved by an insulating sub-layer, such as silicon dioxide formed by any known SOI technique.

Known electro-optic modulators utilise optical phase shifting produced by the electro-optic effect, that is to say the change in refractive index exhibited by an electro-optic material to which an electric field is applied also results in a phase change for light propagating in the material. An alternative electro-optic effect is observed by modulation of refractive index by free carrier density modulation. A simple phase modulator may, therefore, be formed on a rib waveguide by controlling the applied voltages, and hence the number of free carriers in the waveguiding channel. For example, a known electro-optic modulator consists of an elongate diode formed on a rib waveguide. The diode can be either

forward biased (to inject minority carriers into the waveguide), or reverse biased (to deplete the waveguide of carriers). Although injection and depletion diodes are effective modulators, they do have disadvantages. In particular, the speed of the injection diode is limited, and high (>10mA) injection currents are required.

In a recent proposal (L Friedman, R A Soref and J P Lorenzo - Silicon double-injection electro-optic modulator with gate control - J Appl. Phys 63, 1831 - 1988), a dual-injection field effect transistor (DIFET) structure is suggested for phase modulation. In this case, electrons and holes are simultaneously injected into the waveguiding channel via a cathode and an anode. A voltage applied across an elongate gate, which is positioned between the anode and the cathode, controls the density of free carriers, and hence phase modulation. The anode:channel:gate structure of this device forms a bipolar junction transistor biased into the forward active region. In the preferred structure, which has a heavily-doped confining layer of opposite type to the channel, the buried layer forms a further (lower) gate enhancing the bipolar transistor action. When the channel is n-type, the anode is the emitter, the channel forms the base (with the cathode as a remote base contact) and the lower gate is the collector. The minority carriers (holes) injected into the channel will be swept into the collector, instead of being stored. As a result, very few electrons will be injected by the cathode and there will only be a very small change in the index of the guide.

The present invention provides an electro-optic bipolar phase modulator comprising a waveguiding channel which is defined by a lightly-doped silicon layer and which is laterally and vertically confined, the modulator being provided with first, second and third electrodes for

controlling the carrier density within the channel, thereby modulating light propagating in the channel by varying the refractive index of the channel, the three electrodes defining a bipolar transistor structure in which the channel forms an extended base, wherein modulation is achieved by alternating between first and second predetermined voltage regimes applied to the electrodes, the first predetermined voltage regime driving the bipolar transistor structure into the saturation mode, and the second predetermined voltage regime driving the bipolar transistor structure into the cut-off mode.

In a preferred embodiment, the waveguiding channel is vertically confined by means of a heavily-doped sub-layer of opposite polarity to the lightly-doped silicon layer. Alternatively, the waveguiding channel is vertically confined by an insulating sub-layer, such as silicon dioxide, formed by any known SOI technique.

In a preferred embodiment, the first predetermined voltage regime is such that the channel is fully open, the second predetermined voltage is such that the channel is fully depleted, and the alternation between the two predetermined voltage regimes is of a quasi-digital nature.

Advantageously, the first electrode is an emitter and the second electrode is an injector (base contact), the first and second electrodes being formed in the lightly-doped silicon layer, and the third electrode is an elongate collector extending between the emitter and the injector, the base of the transistor structure being constituted by a portion of the lightly-doped silicon layer which extends between the emitter and the injector. Preferably, the collector is a heavily-doped region formed within the lightly-doped silicon layer.

Conveniently, the heavily-doped silicon sub-layer is a p^+ layer, the lightly-doped silicon layer is an n^- epilayer, the injector is n^+ and the emitter and collector are each p^+.

A buried collector may be formed in the heavily-doped silicon sub-layer. The buried collector may consititute the collector of the transistor structure.

Advantageously, the first predetermined voltage regime is such that the resulting channel voltage is at the most 0.2 volts.

Preferably, the length of the device is at least 360μm for a current density of less than 1000A/cm^2.

In a preferred embodiment, a mesa-etched rib formed in the lightly-doped silicon layer constitutes the lateral confinement of the waveguiding channel.

The invention also provides a multi-element modulator constituted by a plurality of modulator elements, each of which is as defined above.

In this case, the modulator may be made into one branch of a long-tailed pair circuit, whereby the modulator is operated using switched constant currents in the open-channel states. Alternatively, the modulators may act as a Mach Zehnder modulator, the modulator being incorporated, half in each branch of a long-tailed pair circuit.

The invention will now be described in greater detail, by way of example, with reference to the accompanying drawings, in which:-

Fig. 1 is a schematic perspective view of a single element phase modulator constructed in accordance with the invention;

Fig. 2 is a simple circuit diagram modelling the modulator of Fig. 1;

Fig. 3 is a schematic perspective view of a multi-element phase modulator constructed in accordance with the invention;

Fig.4 is a diagram of a long-tailed pair circuit incorporating a modulator constructed in accordance with the invention;

Figs 5a to 5c are schematic diagrams showing operating voltages and resultant phase changes for the circuit of Fig.4;

Fig.6 is a schematic diagram illustrating the operation of a Mach Zehnder modulator;

Fig.7 is a diagram of a long-tailed pair circuit incorporating a Mach Zehnder modulator constructed in accordance with the invention; and

Figs.8a to 8c are schematic diagrams showing the operating voltages and resultant phase changes for the circuit of Fig.7.

Referring to the drawings, Fig. 1 shows a silicon bipolar phase modulator built in to a rib waveguide. The waveguiding channel is constituted by a mesa-etched rib 1 formed in a lightly-doped n^- silicon epilayer 2 formed on a heavily-doped p^+ silicon layer 3. The phase modulator has a bipolar transistor structure, having a p^+ emitter 4, an n^+ injector (base contact) 5, a p^+ collector 6 and a base 7 constituted by that portion of the epilayer 2 underlying the emitter, the collector and the injector. The emitter 4, the injector 5 and the collector 6 are formed by any known appropriate techniques. The p^+ layer 3 constitutes a buried collector.

In use, the emitter 4 is the source of holes in the channel 1, and the injector 5 is the source of electrons. The aim of the device to give a high electron population in the channel 1 without a high collector current, and it

is for this reason that the electrode 5 is referred to as an injector rather than as a base contact. This terminology reflects the primary function of the injector 5, namely to provide a high electron density in the channel 1. Any uncombined minority carriers (holes) flow to the collector 6.

The modulator works by alternating between open-channel and depleted-channel states, a quasi-digital phase shift being required to switch between these states. The quasi-digital nature arises because control (using the collector 6) is digital but the magnitude of the resultant phase shift is analogue and dependent upon the applied channel voltage. One path length is due to a fully-depleted channel 1, and the other path length is due to a fully-open channel.

In the open-channel state, it is necessary to store as much charge (of both majority and minority carriers) in the channel 1 as possible. This can be achieved by operating the transistor in the saturation mode, whence the minority carriers (holes) are trapped in a potential well in the base 7, rather than being swept efficiently to the collector 6. In this device, with a large "extrinsic" base region 7, a large electron density will also be stored. As in all transistors, the saturation mode can be characterised by a small collector current, but at the expense of an increased base current. This is exactly the goal of the phase modulator.

Although, in the embodiment described above, reference is made to the waveguiding channels being formed in a lightly-doped n^- silicon epilayer formed on a heavily-doped p^+ silicon layer (whereby the resultant transistor structure is pnp), it will be apparent that the doping could be reversed so that an npn transistor structure would result.

Fig. 2 shows a simplified electrical model for the phase modulator, and it is clear that careful control is required to saturate the transistor without turning on the injector: collector diode. The consequences of this restriction are discussed below.

At the other extreme, it is necessary to deplete the channel 1 fully, and the most efficient way to achieve this is to force the transistor into the cut-off mode, which necessitates reversing the bias on both junctions. The collector:injector junction only needs to be switched from weakly forward-biased just into reverse bias, but a large reverse bias is preferable, because all the carriers (not just those injected) will then be depleted out as both depletion edges in the channel 1 meet. Similarly, it is only necessary to turn the injector:emitter junction off, but switching to a large reverse bias will offer the advantage of a very large field to accelerate the majority carriers (electrons) from the edge of the emitter 4 to the injector.

The requirement for the open-channel modulator to operate in the saturation mode sets limits on the operating voltage, and consequently on the allowed phase change in the device. Denoting the injector voltage measured with respect to the emitter electrode as V_{ie}, this is given by:

$$V_{ie} = - V_{bi} - V_{ch} \qquad \ldots.(1)$$

where V_{bi} is the built-in junction voltage , and V_{ch} is the channel voltage. Now, at all points along the channel 1, the collector: channel junction must be heavily conducting, otherwise hole injection will occur at the collector 6 instead of at the emitter 4. The onset of conduction of this junction arises at point B in Fig. 1.

This demand is equivalent to stating that the diode in the model of Fig. 2 is not heavily conducting. Using V_{ce} as the collector:emitter voltage, at point B on the collector we have:

$$V_{ce} < V_{ie} + V_{bi} \qquad \ldots.(2)$$

At the other extreme, to prevent the direct injection of holes from the emitter 4 to point A on the collector 6, the collector voltage must not exceed the saturation voltage, V_{cesat}. This is current dependent, but is typically - 0.2 V for a low value of I_c. Combining this with equations (1) and (2) gives a limit on the allowed channel voltage:

$$V_{ch} < - V_{cesat} < 0.2 \text{ V} \qquad \ldots.(3)$$

To calculate the phase change of the modulator, we may assume that the electron and hole concentrations in the guide (n and p respectively) are approximately equal, whichever state is being considered. We need only consider the carrier levels when the guide is open, assuming that there is zero carrier density in the other state. Published data on the variation of refractive index, N, with carrier concentration (measured in cm^{-3}) suggest that:

$$\delta N = - \beta \left\{ \left[\frac{n}{4E19}\right]^{1.05} + \left[\frac{p}{4E19}\right]^{0.81} \right\} \qquad \ldots.(4)$$

where β is wavelength dependent, and is 0.03 for 1.3 μm and 0.04 for 1.55 μm. If we may assume that the carrier density will not exceed 1E19 cm^{-3}, we may simplify this,

to assume a worst case (i.e. smallest) refractive index change of:

$$\delta N = - 1.8E\text{-}21\ \bar{n} \qquad \ldots.(5)$$

At 1.55 μm, and with a carrier density of 1E18 cm^{-3}, this will be underestimated by 30 per cent, and, at a lower carrier density of 1E17 cm^{-3}, this will be further underestimated by some 50 per cent or so. Now, a device of length L will produce a phase shift $\delta\phi$, where:

$$\delta\phi = 1.8E\text{-}21\ \frac{2\pi}{\lambda}\ L\ \bar{n} \qquad \ldots.(6)$$

But the mean carrier density in the guide is given by:

$$\bar{n} = \left[\frac{\mu_n\ (n_o - p_o)\ V_{ch}}{B_r\ (b+1)L^2}\right]^{0.5} \qquad \ldots.(7)$$

in which μ_n is the electron mobility, b is the ratio of electron and hole mobilities, n_o and p_o are the equilibrium concentrations of electrons and holes, B_r is the recombination parameter and V_{ch} is the channel voltage.

Combining equations (6) and (7), we see that the phase shift is independent of modulator length:

$$\delta\phi = - 1.8E\text{-}21\left[\frac{\mu_n\ (n_o - p_o)}{B_r\ (b+1)}\right]^{0.5}\ \frac{2\pi}{\lambda}\ \sqrt{V_{ch}} \qquad \ldots.(8)$$

Using known parameter values, and applying the condition of equation (3), we may infer that the maximum phase shift from the modulator is = 0.8 π. Moreover, from

equation (8), the current density, J, in the guide may be obtained.

$$J = \frac{8\,(b+1)^2\, e\, B_r}{9\, b\,(n_o - p_o)} \quad \frac{(-\delta\phi)^3\, \lambda^3}{(3.6E\text{-}21\pi)^3} \quad \frac{1}{L^2} \qquad \ldots.(9)$$

Equation (9) may be used to calculate the minimum length device for a given current density and phase change. At the maximum phase change of 0.8π, the minimum length allowed for a current density of less then 1000 A/cm^2 is 360 μm.

As mentioned above, the bipolar modulator is restricted to operation in the saturation and cut-off modes, so that the phase change of a single modulator element cannot exceed 0.8π. Since this limit is set by the onset of a significant collector current, the device will operate better if a smaller phase shift is acceptable.

In order to make use of the modulator for large phase shifts, a multiple-element modulator can be used, as shown in Fig. 3. In this device, which is merely exemplary, there are two emitters $4'$, three injectors $5'$, four collectors $6'$ and four bases $7'$. For a given operating voltage, the total phase shift ϕ is, from equation (8), independent of element length, but from equation (9) the current density depends upon the inverse square of length. However, if m elements are used in series, whilst maintaining the overall phase change and total modulator length, each element produces a phase shift of $\delta\phi/m$, and has a length of L/m. Substituting these into equation (9) shows that the current density decreases with increasing number of elements used. Furthermore, as each element becomes shorter, the switching time is correspondingly reduced, so that a

multiple-element modulator is therefore desirable.

One possible problem with such a multiple-element modulator is that the tolerance on the injector voltage decreases with increased element count. One method of partially obviating this problem would be to operate with constant currents in the open-channel state, in preference to constant voltage. In order to do this, the modulator M could be made the load element in one branch of a long-tailed pair circuit (see Fig.4), with the other circuit elements integrated onto the same substrate. In this way, additional circuitry (which could be integrated onto the same silicon substrate) would be required to control the switching of voltages V_1 and V_2 at the same time (V_1 and V_2 being the voltage waveforms applied to the input of the long-tailed pair and the injector electrode of the modulator respectively). The operation of the circuit is illustrated by Fig.5, which shows the operating voltages V_1 and V_2 (Figs.5(a) and 5(b)) and the resultant phase changes (Fig.5(c)) for the circuit.

Fig.6 is a schematic representation of a Mach Zehnder modulator, and shows light (from either an optical fibre or a waveguide) being split equally into two branches and then recombined. Each of the branches is provided with means P_1, P_2 for applying a phase shift to the light passing therethrough. For example, the phase shift means P_1 of the upper branch may apply a variable phase shift of up to $+ \delta\phi$, and the phase shift means P_2 of the lower branch may apply a variable phase shift of up to $- \delta\phi$. When the light from the two branches is recombined, there will be constructive or destructive interference at any given instant depending upon the phase shifts applied by P_1 and P_2.

Fig.7 shows a long-tailed pair circuit which incorporates modulators M_1, and M_2 into each branch of

the circuit, the modulators being of the type shown in Fig.1 and being combined to constitute a Mach Zehnder modulator. In this case, the drive circuit has differential voltages V_1 and $\bar{V}_1$, and V_2 and $\bar{V}_2$ applied in the manner shown. The operation of the circuit is illustrated by Fig.8, which shows the operating voltages V_1 and $\bar{V}_1$ (Fig.8(a)), the operating voltages V_2 and $\bar{V}_2$ (Fig.8(b)) and the resultant phase differences (Fig.8(c)) for the circuit.

CLAIMS

1. An electro-optic bipolar phase modulator comprising a waveguiding channel which is defined by a lightly-doped silicon layer and which is laterally and vertically confined, the modulator being provided with first, second and third electrodes for controlling the carrier density within the channel, thereby modulating light propagating in the channel by varying the refractive index of the channel, the three electrodes defining a bipolar transistor structure in which the channel forms an extended base, wherein modulation is achieved by alternating between first and second predetermined voltage regimes applied to the electrodes, the first predetermined voltage regime driving the bipolar transistor structure into the saturation mode, and the second predetermined voltage regime driving the bipolar transistor structure into the cut-off mode.

2. A modulator as claimed in claim 1, wherein the waveguiding channel is vertically confined by means of a heavily-doped sub-layer of opposite polarity to the lightly-doped silicon layer.

3. A modulator as claimed in claim 1, wherein the waveguiding channel is vertically confined by an insulating sub-layer, such as silicon dioxide, formed by any known SOI technique.

4. A modulator as claimed in any one of claims 1 to 3, wherein the first predetermined voltage regime is such that the channel is fully open, the second predetermined voltage is such that the channel is fully depleted, and the alternation between the two predetermined voltage regimes is of a quasi-digital nature.

5. A modulator as claimed in any one of claims 1 to 4, wherein the first electrode is an emitter and the second electrode is an injector (base contact), the first and second electrodes being formed in the lightly-doped silicon layer, and the third electrode is an elongate collector extending between the emitter and the injector, the base of the transistor structure being constituted by a portion of the lightly-doped silicon layer which extends between the emitter and the injector.

6. A modulator as claimed in claim 5, wherein the collector is a heavily doped region formed within the lightly-doped silicon layer.

7. A modulator as claimed in claim 5 or claim 6, wherein the heavily-doped silicon sub-layer is a p^+ layer, the lightly-doped silicon layer is an n^- epilayer, the injector is n^+ and the emitter and collector are each p^+.

8. A modulator as claimed in any one of claims 5 to 7, wherein a buried collector is formed in the heavily-doped silicon sub-layer.

9. A modulator as claimed in claim 8 when appendent to claim 5, wherein the buried collector constitutes the collector of the transistor structure.

10. A modulator as claimed in any one of claims 1 to 9, wherein the first predetermined voltage regime is such that the resulting channel voltage is at the most 0.2 volts.

11. A modulator as claimed in any one of claims 1 to 10, wherein the length of the device is at least 360μm for a current density of less than 1000A/cm^2.

12. A modulator as claimed in any one of claims 1 to 11, wherein a mesa-etched rib formed in the lightly-doped silicon layer constitutes the lateral confinement of the waveguiding channel.

13. A modulator as claimed in any one of claims 1 to 12, wherein control electronics are integrated onto the same substrate as the silicon layer.

14. An electro-optic bipolar modulator substantially as hereinfore described with reference to, and as illustrated by, the accompanying drawings.

15. A multi-element modulator constituted by a plurality of modulator elements, each of which is as claimed in any one of claims 1 to 14.

16. A modulator as claimed in claim 15, wherein the modulator is made into one branch of a long-tailed pair circuit, whereby the modulator is operated using switched constant currents in the open-channel states.

17. A modulator as claimed in claim 15, wherein the modulator acts as a Mach Zehnder modulator, the modulator being incorporated half in each branch of a long-tailed pair circuit.

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